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TRENDS OF NUCLEAR POWER DEVELOPMENT IN THE USSR

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1. Introduction

On June 27.1954 the first nuclear power plant with a capacity of 5000 kWe was commissioned in the USSR.

The last ten years in many countries were a period of the origin and first practical steps of a new branch of technology peaceful nuclear power, called on to use the fission energy of uranium and plutonium for the benifit of mankind.

The period after the second Geneva Conference is characterised by intensive scientific and engineering research and many practical achievements in the USSR and a number of other countries.

The know-how and experience accumulated so far allow to evaluate more correctly the solved and even more so, unsolved problems and to outline more effective ways of the further nuclear power development under the specific conditions in each country.

2. Progress in Power Engineering Development in the USSR and its Features

The creation of material and technical basis for the communist society in the USSR, the development of industry and agriculture, the increase of energy consumption by population demand expanded construction of electric power stations and higher rate of the power generation . Power production and installed electric capacities in the USSR are correspondingly to amount to :

in 1970 : 900-1000 billion kWh; 180-200 million kW;
in 1980: 2700-3000 billion kWh; 540-600 million kW.

Let us recall that power production in the USSR in 1963 reached 412 billion kWh, while in 1960 it was equal to 292 billion kWh; in 1950 - 91 billion kWh, and in 1940 - 48 billion kWh. For the last few years the annual increase of the production of electrical energy in the USSR was 11-12 per cent. In 1963 the introduction of new capacities equalled 10 million kW.

The large condensing thermal power stations with a capacity to 2400 MW, the combined electric and central heating plants with a capacity of 400 MW and more , large hydroelectric power stations of 4000-5000 MW capacity including the largest hydroelectric power stations in the world on the Angara and Enisey rivers in Siberia are now under construction. Early in 1964 five thermal power stations with a capacity above 1000 MW each have been put in operation; by the end of 1965 the number of such large thermal power stations will be 11; the capacity of one of them will exceed 2000 MW. The integrated power system of the European part of the USSR, the total capacity of which by 1965 will exceed 50 million kW has been created /1/ .

The construction of large, typical in design , thermal power stations consisting in 200-200-500-800 MW units with higher steam conditions (130-240 at and 560-580°C), the wide use of prefabricated reinforced concrete elements in the building construction, the large-scale production of standard power equipment, the successful construction of long transmission lines with a voltage of 500 kV, with transmission capacity up to 1 million kW, all this contributes to a constant improvement of the economis of conventional power engineering, to a decrease of specific capital costs and generation costs.

This continual engineering progres in modern thermal power engineering should be taken into account in determining the economy and competitiveness requirements for nuclear power plants in the Soviet Union.

The studies of the power and fuel balance of the country with taking into account the newly discovered deposits of fuel shows that power demands in the USSR will be covered with organic fuel and hydropower for a long period of time. However the uneven distribution of the organic fuel resources causes a substantial increase in the cost of the electrical energy production in a number of districts of the country, for example in the European part of the USSR.

There are several ways of satisfying the growing,power demands in the European part of the USSR: the construction of thermal power stations and providing for their fuel supply by increasing the production of expensive coals in the Donets Coal Basin or the railroad transportation of cheaper coals from Siberia; 2) the construction of powerful transmission lines from Siberia to Europe; 3) the construction of nuclear power plants on a sufficiently large scale, defined by their competitiveness.

The task of the further development of power supply systems in the European districts of the USSR for the nearest 10–20 years can be solved by combining all the three techniques in varying proportions.

Thus the problem of nuclear power development in the Soviet Union at present is in the first place the problem of the choice of the most economical way of satisfying the power needs in the districts unpriviledged as far as organic fuel and power supply go.

These circumstances stipulate to continue the accumulation of engineering experience and a thrcugh study of the prospects for nuclear power development with the necessary research and development untill the necessary level of nuclear power plants competitiveness is reached.

With high rate and tremendous scale of the power plants construction in the USSR an appreciable economy can be obtained through the use of nuclear power plants when they form an important portion in the overall growth of new power capacities.

In connection with this it is necessary to evaluate and to choose the most effective way of the development of large nuclear power industry and on this basis to outline a long-run programme of its development in the country.

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3. Nuclear Power Development in the USSR

The total capacity of nuclear power plants in the Societ Union for the current year will exceed 900,000 kWe . The nuclear power plants with the total electrical output of several millions kilowatt are supposed to be put in operation in the USSR by 1970; the period to 1970 is considered as a period of development and construction of large-scale prototypes for the further transition to increasing serial construction of large nuclear power plants in 1970-1980.

To date the 100 MWe first unit of Beloyarsk I.V.Kurchatov nuclear power plant with nuclear steam superheat has been put in operation and is in the stage of pilot operation. The first 210 MWe unit at Novovozonezh nuclear power plant is in the stage of commissioning /2,3/. The Siberian nuclear power plant intended to operate at 600 MWe has exceeded it design capacity. The construction and commissioning of these stations has provided rich experience in design, installation and production of reactor equipment and materials for large water-moderated water-cooled and uranium-graphite power reactors including reactors with nuclear steam superheat. The second 200 MWe unit of Beloyarsk nuclear power plant is being constructed. The construction of the second unit with a capacity of 365 MWe at Novovoronezh nuclear power plant began.

Further development of reactors of the types mentioned aimed at improving their economy is being carried in the direction of unit capacity increase with simultaneous increase in the mean burn-up to 15.00-20.000 MWd/t and the use of other modifications /4,5/ . The dynamics of the expected change of economical data for Novovoronezh and Beloyarsk nuclear power plants is given in Fig.1. The high specific capital investment in the construction of the first units may be explained to a considerable degree by relatively small reactor capacities , by the expenditures on the construction site of nuclear power plant and the high cost of experimental and pilot equipment.

The ten years' experience of the first nuclear power plant and faultless operation of a 5000 kW sodium-cooled

BR-5 fast reactor in Obninsk during six years showed that it is possible to obtain, with representative reactor tests, "power" burn-up of UO_2 and PuO_2 fuel equal up to 60000 MWd/t i.e. the value sufficient to generate competetive power on large nuclear power plants , both with thermal - and fast reactors.

In the nearest months a 50-75 MWe nuclear power plant with boiling water reactor at the town of Melekess will be put in operation[6].

The prototypes of small mobile nuclear power plants are in operation: TES-3 with water-moderated water-cooled reactor with a capacity of 1,5 MWe at Obninsk and "ARBUS" with 750 kWe organic reactor at Melekess, intended to be used in remote districts of the country to which fuel transportation is difficult and uneconomical /7/ .

The world's first peaceful nuclear ship the icebreaker "Lenin" with three pressurised water reactors with a capacity of 90 MWth each is successfully continuing its its fifth navigation. Last year after three-year operation without refueling , cores of all reactors were successfully replaced. The new cores have even a longer life-time. The reliable operation of the icebreaker "Lenin" power plants during five years has confirmed the safety of her nuclear reactors in all operating conditions /8/ .

4. Fast Reactors

Research and development carried out in the field of reactor physics and fuel elements, the experience with the sodium coolant technology and the successful development, construction and testing of pilot equipment for sodium loops made it possible to abandon the earlier planned construction of 50 MWe fast reactor. Recently it was decided to build a fast reactor (BN-350) with a capacity of 300-350 MWe /9/.

The breeding ratio in this reactor during the initial period of operation as a uranium converter will by 1.1 and will gradually increase to about 1.5 after transition to the operating conditions of a plutonium breeder. Burn-up at the initial period of operation is supposed to be equal to 5-6 at. per cent and will increase eventually due to the use of fuel elements with directed removal of fission products, to 8-10 at. per cent.

The intensification of heat removal in reactor core, the sodium temperature increase at reactor outlet to 600-630°C, the increase of the coolant heating in the reactor as well as the burn-ups obtained permit to hope that in the future 500-600 MWe completative power reactor can be developed on the basis of the BN-350 type. Such reactor is expected to be a further step in the development of fast breeders considered by us as the main road for the development of nuclear power in the USSR. The estimates of economical data for fast reactors and approximate dynamics of their change are presented in Fig.2.

5. 1000 MWe Nuclear Power Plants

In the USSR work on further improvements of nuclear power reactors is in particular directed at finding out the possibilities of a major increase of reactor unit capacities to 1000 MWe as well as at the development of optimal converters which will provide speediest possible introduction of U-238 in the fuel cycle.

The design and development works carried out in the USSR cofirm, on the basis of the available experimental data, the technical possibility of constructing a uranium-graphite reactors cooled by water at supercritical conditions or gas (CO) coold reactors with unit capacities of the order of 1000 MWe as well as fast sodium reactors with breeding ratio of 1.7 with the breeding in the core close to 1. The steam conditions at nuclear power plants with the above reactor types will approach the conditions achievable by modern conventional power stations.

The above unit capacities would provide the reduction of specific capital costs and operational costs and secure the production of competetive power.

The unit capacities of 1000 MWe and higher can be also obtained in uranium-graphite reactors cooled by pressurised water at lower parameters with possible simultaneous use of the removed heat for the purposes of water desolination or heating.

6. Reactor-converters

The most efficient reactor-converters, as it should be expected are natural uranium reactors moderated by heavy water and cooled by carbon dioxide (of the type being built in the Chechoslovak Socialist Republic) or by organic coolant. A highly efficient converter is a fast reactor with sodium or gas coolant especially with the time of fuel being outside the reactor about eighteen months to two years or less.

The research and development on the 400-500 MWe reactor with heavy-water moderator and organic coolant showed that to secure good economical features for such a reactor certain technical difficulties are to be surmounted which are connected with necessity of the provision thermal and radiation stability of the organic coolant, the impossibility to obtain high steam conditions, the complexity of technology scheme due to the great number of loops.

As the design experience as well as calculations and research on 350-400 MWe gas-graphite reactor show, a number of problems, corresponding to heavy-water moderated organic-cooled reactor, in this case do not exist. However, high burn-ups necessary for acquiring competitiveness are difficult to achieve because graphite is worse as moderator, whereas the use of oxide fuel for this purpose is possible only with slightlyenriched uranium and at a lowered conversion ratio. A serious problem is to obtain the economically necessary burn-up to 7,000 to 10,000 MWd/t for metallic uranium and its alloys.

From this point of view a great promise is held in the use of small diameter rod-type fuel elements based on slightly alloyed uranium which has undergone a special thermal treatment to obtain a satisfacrory dimensional stability under irradiation.

A heavy water-gas cooled 150 MWe reactor being built by the Czechoslovak Socialist Republic with the participation of the Soviet Union, is designed to use this type of fuel elements.

Design, construction and operation of this reactor as well as the engineering experience obtained with the production and operation of the equipment, systems and instruments for heavy water and gas loops of atomic power station will also provide information in an industrial scale on obtainable burn-up for rod fuel elements.

The requirements of unit power capacity increase up to 800-1,000 MWe and high steam conditions (pressure above 90 atm. and temperature above 500°C) with the most effective use of the nuclear fuel and intensive introduction of uranium-238 and thorium into the fuel cycle are better met by the fast reactor-converter which gradually passes to operation as a breeder reactor. Such a plant may have a single design for both the converter and breeder modes of operation and for use of uranium as well as thorium as fuel. For both fuels the characteristics of the reactor are quite satisfactory at all operational conditions (see Table 1) /10/.

7. Economic analysis for individual power stations insufficient

The above considerations pertain to technical possibilities and economic characteristics of individual reactors and nuclear power stations. Both the experience gained and literature published testify, however, that economic characteristics of individual nuclear power stations do not give the correct notion of their status in the national economy or enable one to choose the most profitable way for the development of national nuclear power; these are to a considerable, sometimes decisive degree, dependent on subjective factors such as rent prices for nuclear fuel or credit for plutonium, etc.

What is required is a scientific approach, an analysis of technological, economic and raw material data which would make it possible to find the objective proportions and relationships between different types of industries involved in and servicing the system nuclear power. The possibilities of this system should be set against the alternative ways of satisfying the power demands of the country of its regions to find the most advantageous way for the development of power engineering in the specified district and period of time.

The industries involved in the system of nuclear power such as uranium mining and enrichment, chemical processing of irradiated fuel elements, reenrichment of spent nuclear fuel, production of fuel elements out of fresh or spent nuclear fuel should be treated as the own needs of the nuclear power. Spent fuel and the plutonium produced should also be treated as materials to be used by the system itself according to their value as fuel and neutron source.

8. Economics of nuclear power as an industry

In 1961-1963 a technological and economic analysis of prospects for development of the nuclear power industry was made in the Soviet Union on the basis of the experience gained in the design construction and operation of nuclear plants and "fuel cycle" installations.

Investigation was made on the possibilities and necessary conditions for obtaining competetive characteristics for the whole system of industries involved in nuclear power development including nuclear power plants and the allied industries. Comparison was made with the development of conventional power industry; the necessary expansion of fuel resourses and transportation means was also taken into account.

A considerable number of possible ways for further development of nuclear power was considered in terms of the type or combination of types of reactors used, rate of improvement of their basic characteristics, size and rate of growth of the industry up to 1980 as well as in terms of operating conditions in the "fuel cycle" installations. It is impossible to report all the results in this paper; some of them, however, are cited below. Table II presents data on expected progress in the basic characteristics of various reactor types.

These data were the line of departure for one of a series of calculations and investigations.

The analysis made enables us to come to certain conclusions on possible development of nuclear power in the Soviet Union.

1) Nuclear power, being a newly developing branch of power engineering will at the first stage be able to compete with conventional power plants in the areas with relatively high cost of power production. With technological improvement of nuclear power plants and improvement of their economic characteristics the areas where they can compete will expand.

For European districts of the USSR, where the Donets coalfield will provide the fuel, the estimated total specific investments in the construction of conventional stations, coal mines and coal transportation are rather high for the period 1970 to 1980; the larger part (50 to 60 per cent) have to be spent on mining and transportation and only 40 to 50 per cent on construction of power stations.

If the development of nuclear power in this part of the country is to be economically justified as compared with other power sources, at least the following targets must be reached

Total specific investments in nuclear power stations and allied industries, in roubles per kW	Production cost of power at nuclear power stations, in kopecks/kWh
150-160	0.40-0.45
or 170-180	0.37-0.42
or 190-200	0.33-0.38

These objectives can be achieved if the power of each reactor is increased up to 500.1000 MWe, efficiency to 35 to 40 per cent, burn-up to 30,000 to 40,000 MWd/t in thermal reactors and to 60,000 to 100,000 MWd/t in fast reactors. Such burn-up characteristics are evidently difficult to obtain in fuel elements where metallic uranium or its alloys are used, but it is feasible for ceramic (oxide or carbide) fuels. Besides, provision should be made for serial production of all equipment elements and necessary materials as well as for a rational, highly mechanized and automated for mass production, manufacturing of fuel elements and processing of spent nuclear fuel with the time of the fuel being outside the reactor not more than 18 or 24 months.

2. Most profitable (see Tables III and IV) and at the same time providing for the most effective use of nuclear fuel is a development of nuclear power with the priority given to fast 500 to 1000 MWe reactors with a mixed uranium and plutonium fuel cycle and the increase of the proportion of plutonium breeder reactors.

Such a trend would require small scale industries for production and chemical reprocessing of core fuel elements and moderate capacities for production and chemical reprocessing of blanket fuel elements as well as for reenrichment of the core fuel with the plutonium produced in the reactor, enriched fuel being required only to provide the initial load of every new reactor and one or two its refuelings.

No constant expansion of uranium mining or enrichment industries will be required; nor practically will the power industry be dependant on these , because two or three sets of fuel cores are a sufficient "trigger pulse" for further operation of reactors that would be self sustaining and at the same time provide a certain plutonium excess for new capacities at the rate of eight to ten per cent of annual power increase. This rate can be considerably increased through the use of fissionable materials formerly intended for defence purposes. Such possibilities are opened up in the Statement made by N.S.Kruschchev, Chairman, USSR Council of Ministers on the 21st April 1964.

The magnitude of the "Trigger pulse" increases practically in proportion to the power of the reactor introduced and amounts about 18.0 to 25.0 tons of uranium enriched up to about 20 per cent for every 1.000.000 kWe of newly introduced power (for a competitive reactor).

For every million kilowatts of new power it is necessary to have "fuel cycle" installations which would chemically process and produce mixed uranium and plutonium fuel elements up to six or eight tons annually for the core and up to 20-25 tons annually for blanket uranium or thorium.

Table V presents comparative data on production capacity of "fuel cycle" installations which correspond to 1.000.000 kWe for different types of reactors.

3. Analysis of production structure in the system of nuclear power showed that the proportion of capital investment in the fuel cycle does not exceed 20 to 30 per cent at the low capacity of nuclear power at its initial stage of development and can be brought down to 10-15 per cent with the increase of the total nuclear power stations capacity.

This will be one of the basic economic advantages of the large-scale nuclear power due to high thermal capacity of nuclear fuel.

This advantage is responsible for the result of our prelimenary estimations; which is that the operation of nuclear power stations and the "fuel cycle" installations will require, when nuclear power is well expanded lower labor consumption as compared with operation of the same class of conventional coal-fired power stations and related coal mining and transporting facilities;this in the long run characterizes the higher productivity of labour, an inherent characteristic of nuclear power industry.

9. Conclusions

The most promising direction of a large-scale nuclear power development should be the preferable construction of fast reactors which will in the initial period operate as converter-reactors and pass gradually to breeding operation with a short (about five years) time of doubling the amonnt of nuclear fuel.

Construction of a certain number of nuclear power stations with thermal reactors of which a considerable engineering experience has been to date accumulated are considered advantageous in the areas where it will be economically justified for several coming years.

Along with the construction of reliable and economical nuclear power stations it is important to develop simple and cheap techniques for treatment of irradiated fuel and waste disposal in the industrial scale. Before such technology is developed, the storage for a reasonable time the spent fuel elements with low content of valuable isotopes may prove economical.

The expansion of nuclear power will open up wide perspective for both developed and developing nations. It will considerably increase productivity of labour in power industry, reduce fuel transportation, make national power industry more independent of fuel mining and transportation which is particularly the case for countries with limited resources of organic fuel, substantially cut the cost of power in the areas where fuel is expensive, and create favourable conditions for a wider development of industries and resourses in these areas, use the energy of fission products radiation to develop entirely new technological processes in chemistry and other branches of the national economy.

In all probability, in those areas of the USSR where fuel is expensive, nuclear power will be after 1980 one of the important directions of power engineering development. By 1980 the total electrical capacity of nuclear power plants in the USSR can be presumably estimated as amounting to tens of millions of kWe .

It is quite grounded to believe that the coming 10-15 years will see a wide development of economical nuclear power.

294

Table I

CHARACTERISTICS OF A FAST BREEDER-CONVERTER

Characteristics	Core: uranium 235+ +uranium 238 blanket natural or depleted uranium	Core: plutonium 239 +uranium 238 blanket natural or depleted uranium	Core: uranium 235 +uranium 238 blanket: thorium	Core : uranium 235 + plutonium 239 + uranium 238 blanket thorium
Electric power, MW	500	500	500	500
Efficiency(gross), %	42	42	42	42
Steam pressure, kg/cm^2	130	130	130	130
Steam temperature, $^\circ$C	565	565	565	565
Conversion ratio	1.20	1.50	1.15	1.35
Loading of fissionable isotope, kg	1290	1140	1300	1010

294

Table II

EXPECTED IMPROVEMENT IN THE CHARACTERISTICS OF REACTORS WITH THE INCREASE OF THEIR UNIT CAPACITIES FROM 300 to 800 MW

Characteristic	Gas cooled graphite naturual uranium reactors	Heavy water organic cooled natural uranium reactors	Water-cooled graphite slightly enriched-uranium reactor with steam superheating in the core	Water cooled water-moderated slightly enriched-uranium reactors	Fast sodium reactors	
					uranium convertor	plutonium breeder
Efficiency (gross),%	35-37	30-33	40-45	30-33	40-42	40-42
Initial concentration of fissionable isotopes, kg/ton	7.14	7.14	30-50	30-50	190	150
Fission products built up, kg/t	3.6-5.2	3.6-7.7	30-40	30-40	50-100	5-100
Conversion ratio	0.5-0.6	0.7-0.8	<0.4	<0.4	1.1-1.2	1.5-1.6

294

Table III

ESTIMATED STRUCTURE OF MEAN SPECIFIC CAPITAL INVESTMENTS IN THE DEVELOPING NUCLEAR POWER INDUSTRY FOR DIFFERENT TYPES OF REACTORS

Type of investment	Gas-cooled graphite natural uranium reactors	Heavy water organic natural uranium reactors	Water cooled graphite slightly enriched-uranium reactors with steam superheating in the core	Water-cooled water-moderated slightly enriched-uranium reactors	Fast sodium reactors
Investments in nuclear power stations, %	75	80	66	66	79
Investments in fuel cycle installations, %	25	20	34	34	21
Mean unit investments in nuclear power industry including fuel cycle, roubles per kW	239	232	173	205	161

294

Table IV

ESTIMATED STRUCTURE OF MEAN POWER PRODUCTION COST FOR DEVELOPING NUCLEAR POWER DIFFERENT TYPES OF REACTORS

Type / Structure details, percentage	Gas cooled graphite natural uranium reactors	Heavy water organic natural uranium reactors	Water-cooled graphite slightly enriched-uranium reactors with steam super-heating in the fuel core	Water-cooled water-moderated slightly enriched-uranium reactors	Fast sodium coolant reactors
Depreciation plus maintenance, %	77	29	45	49	65
Fuel cycle cost ,%	11	10	48	45	25
Wages,etc., %	12	11	7	6	10
Mean power production cost kopeks/kWh	0.40	0.42	0.43	0.48	0.33

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294

Table V

CHARACTERISTICS OF FUEL CYCLE FOR REACTORS OF DIFFERENT TYPES PER 1000 MWe of POWER

Reactor type	Operating concentration of fissible isotope, kg/ton	Required yield of produced and chemically processed fuel elements, **tons/year**	Start up consumption of uranium for three years prior to regenerate and plutonium return, tons	Annual consumption of uranium after the return of regenerate and plutonium, tons/year
Natural uranium reactors				
Gas cooled graphite and heavy water organic reactors	up to 7	130-170	800-1000	40-100
Slightly enriched-uranium reactors				
Water-cooled water-moderated and water-cooled graphite reactors with nuclear superheating of steam	up to 50	20-25	80-100	16-20
Fast reactors (fuel cores)	up to 200	6-8	18-25	None; excess plutonium produced
Fast reactors (blanket)	up to 7	20-25	80-100	less1.0

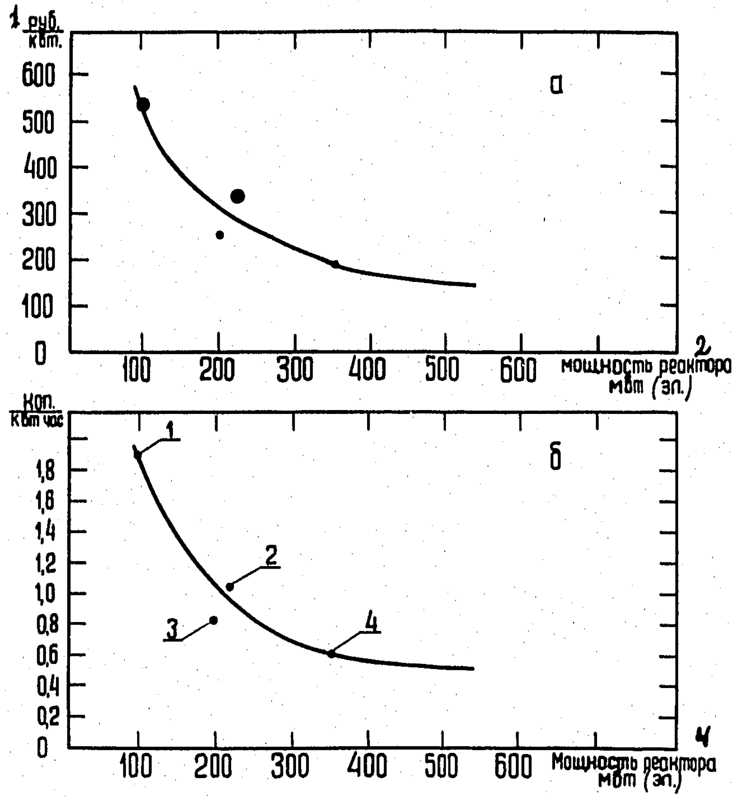

Fig.1. Economic characteristics of Beloyarsk and Novovoronezh nuclear power plants

a) Capital costs per 1 kWe

• - estimate

⊙- actual costs

b) power generation cost:

1 - the first unit, Beloyarsk nuclear power plant

2 - the first unit, Novovoronezh nuclear power plant

3 - the second unit, Beloyarsk nuclear power plant

4 - the second unit, Novovoronezh nuclear power plant

1. rubles/kW
2. reactor capacity, MWe
3. kopecks/kWh
4. reactor capacity, MWe

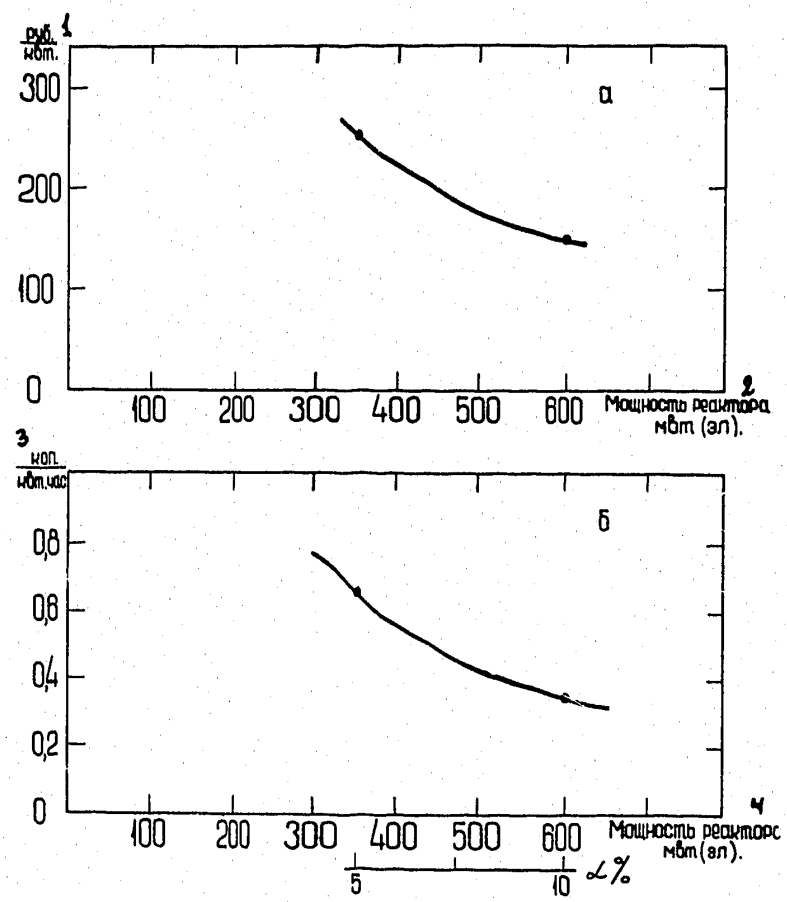

Fig.2. Economic characteristics of fast sodium reactors (estimate)

a) capital costs per 1 kWe

b) power generation cost

- fission products build up, atomic per cent

1. rubles/kW
2. reactor capacity, MWe
3. kopecks/kWh
4. reactor capacity, MWe

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